Inorganic Fertilizer vs. Cattle Manure as Nitrogen Sources for Maize (*Zea Mays* L.) in Kakamega, Kenya

An Undergraduate Honors Thesis

Melissa Herman

Advisor: Dr. Rattan Lal

School of Environment and Natural Resources

The Ohio State University

29 May 2009

Table of Content

Abstract

Despite worldwide efforts, Sub-Saharan Africa's (SSA) food security has not improved since 2000 when the United Nations published its Millennium Development Goals. There are many reasons, but inconsistent and inefficient soil management by farmers is a major contributing factor. Maize (*Zea Mays* L.) is one of the major staple foods in Kakamega, Kenya, a large agriculture community located in Kenya's Western Providence. Nitrogen (N) is an essential nutrient for plant growth and a limiting factor affecting crop yield. However, fertilizer is often unavailable to farmers due to high prices, and manure is not available in sufficient quantity and at appropriate times. Therefore, the objective of this study was to compare organic and inorganic sources of N in relation to maize yields and soil quality in Western Kenya.

The project began in April 2007 when the maize was planted at four farm locations within the Kakamega District. Cattle manure was applied to half of the plots at each farm site, and inorganic fertilizer was applied to the remaining plots, both in accordance to nutrient recommendations from the Kenya Agricultural Research Institute's (KARI) Regional Research Center in Kakamega. The N rate from the inorganic fertilizer was equivalent to the dry-weight rate of total-N applied in the cattle manure, allowing for a direct comparison.

The data on soil, plant analyses, and crop yields showed that inorganic fertilizer produced grain yields 68% higher than that from manure. However, yields were low. Analysis of maize leaves at initial silking stage showed that many nutrients were below the critical levels. Further estimates show that up to twice the amount of N applied to the field is exiting the field via maize grain and stover, thereby creating a negative nutrient budget. For these reasons, it can be concluded that the recommended N rate of 50 kg/ha is not enough to either sustain crop yields or restore the degraded soil systems.

Acknowledgements:

I thank my academic advisor, Dr. Rattan Lal, for his continual supervision and support throughout this study. I also thank Dr. Don Eckert and Dr. Frank Calhoun for serving on my defense committee. I specially thank Christine Omboko (KARI-Kakamega) for coordinating this experiment with the Kenyan farmers and for her assistance with field work; Shane Whitacre (SENR) for his supervision and assistance in the soil chemistry lab; and Ji Young Jung (SENR) for her supervision and assistance with the statistical analysis.

I also thank the following people and organizations for funding support: OSU Office of International Affairs, OSU Libraries, OSU Undergraduate Student Government, Golden Key International Honor Society, Dr. R. Mullen (SENR-OARDC), and Dr. R. Lal (SENR).

Introduction

In 2000, the United Nations launched its Millennium Development Goals, creating a strategic plan for addressing problems such as health, education, equality, and environmental sustainability in countries classified as developing (United Nations, 2008). This plan comprises eight goals to be achieved by 2015. The first of these goals is to eradicate extreme poverty and hunger; specifically: 1) halve, from 1990 to 2015, the proportion of people whose income is less than one dollar a day, and 2) halve, from 1990 to 2015, the proportion of people who suffer from hunger. In the United Nation's 2008 report, it was stated that little progress if any had been made in reducing the level of poverty in Sub-Saharan Africa (SSA).

It is predicted for the world population to rise from 6.1 billion in 2000 to 8.9 billion by 2050 (United Nations Economic and Socials Affairs, 2004). Most of this growth is predicted to occur in developing regions of the world, of which Africa shows growth predictions considerably higher than any other region. Current increases in food and commodity prices, having the greatest impact on the world's poor, could result in an additional 100 million people worldwide living in extreme poverty (United Nations, 2008). Most of this is projected to occur in SSA and South Asia; these regions are also ranked highest for numbers of political refugees, which is greatly contributing to their levels of poverty. The UN does not expect to reach its first goal in SSA by the year 2015, and considerable efforts will need to be made to ensure the level of poverty and food insecurity does not worsen in upcoming decades.

In 1990, 47% of SSA's population lived on $1 a day (World Bank, 2007). This is based on Purchasing Power Parity (PPP), in which both exchange rate and living standards are taken into account. By 1999, this number had decreased to 46% of SSA's population, and to 41% by 2004. Kenya is located in East Africa and is part of SSA. In 1997, 23% of Kenya's population lived on $1 a day (PPP), and 52% of the population lived under Kenya's national poverty line. Kenya and SSA as a whole have experienced annual population growth rates of 2 to 3% between 1990 and 2007. However, from 2000 to 2004, food production had only increased by 7% in SSA according to its food production index. Kenya has fared better: using 1999-2001 as an index base, food production increased 16% by 2005, and 29% by 2006.

Kenya's population is predicted to increase from 30.5 million in 2000 to 45.8 million by the year 2100 (United Nations Economic and Social Affairs, 2004). Population growth tends to increase demographic pressures for land resources, and increases in food production will need to come from vertical increases in crop production per unit area, time, and resource input, rather than through extensification of land resources (Lal, 2008). However, Kenya's increase in agricultural output is more a result of extensification rather than intensification. Land under cultivation for cereal crops has been steadily increasing in Kenya since about 1960 through 2006 (Fig. 1), but cereal yields have not changed in the 20 years ending in 2007 (World Bank, 2007).

The land's productivity is stagnant or in decline, potentially leading to decreased food security and increased poverty. There are many causes for this dilemma, but poor soil and nutrient management, leading to poor soil structure and declining fertility, are major contributors. When comparing the climate and soil orders of SSA with temperate regions of the world, it is understandable that crop yields are lower on soils of the tropics primarily because many are highly weathered and have low inherent fertility. This is because soils become increasingly susceptible to degradation with an increase in mean annual temperatures and a decrease in mean annual precipitation (Lal, 2009). Soils are prone to further degradation by poor management, which is often driven by desperate, small-landholder farmers who have few resources. The soils of SSA have the capacity and ability to be productive, if managed correctly, as declines in soil quality are more often related to “how” than “what” crops are grown (Lal, 2009).

Maize (*Zea mays* L.) was introduced in Africa by Portuguese explorers during the 16th century, and now is one of Africa’s most important food crops, second only to cassava (*Manihot esculenta*) (Export Processing Zones Authority, 2005). In Kenya, it is the staple food crop, as it is estimated that 1.6 million hectares (mha) are under maize production. More than 70% of Kenya’s maize is grown by farmers owning less than eight ha or 20 acres (Salasya et al., 1998, Export Processing Zones Authority, 2005). Maize is generally considered a food crop and not a cash crop. In Western Kenya, however, maize is also grown as a cash crop, even when production is not high enough to meet consumption needs, because the region’s economy relies so heavily on agriculture (Salasya et al., 1998). When production is high, maize is exported to neighboring countries, but during drought seasons, maize must be imported (Export Processing Zones Authority, 2005). During these periods of crop failure and food importation, more cash crops are grown to balance the foreign exchange, resulting in decreased production of food crops and an even greater stance of food insecurity (Makokha et al., 2001).

In the Kakamega District, the project study location in Western Kenya, the area is only able to produce about 50% of its consumption needs during a normal year (Mwale and Wambua, 2008). Maize production is an important component of Kenya’s food-security as well as its economy. Agriculture contributes 30% of the nation’s GDP. Therefore, it is critical that yields are sustainable and improve if they are to continue to support Kenya’s growing population and potentially spur economic growth. This has not been the case in recent decades (Fig. 2). Maize yields have been stagnant or in decline due to poor government policy and intervention within Kenya’s agricultural sector and insufficient technology transfer to farmers (Groote et al., 2005).

A major limiting factor for nutrient management for Kenyan farmers is access to fertilizers, specifically sources of nitrogen (N) for maize production, as fertilizer use is not consistent (Table 1). In a study conducted by Salasya et al. (1998), 133 farmers in the Kakamega and Vihiga Districts were surveyed, and only 34.6% reported to have used fertilizer, defined as any type of basal or top-dress fertilizer. In contrast, 68% of the surveyed farmers reportedly used manure. Farmers reported high prices as being the reason for not using fertilizer; the high price was also shown to be the determining factor in the amount of fertilizer purchased by those who did use it. Soil fertility, and subsequently crop yields, will greatly suffer when soil nutrients are depleted (Lal, 2009). This occurs whenever nutrient removal from harvest, erosion, leaching, and volatilization, exceed the soil systems nutrient inputs from recycling, biological nitrogen fixation (BNF), animal manure, and fertilizers.

The objective of this study was to compare organic and inorganic sources of N in relation to maize yields and soil quality. Specifically, an N rate from an inorganic fertilizer was compared to an equivalent dry-weight rate of N from cattle manure using six maize plots at four farm sites. All nutrient applications were made according to the management recommendations from the Kenya Agricultural Research Institute's (KARI) Regional Research Center in Kakamega. It is hypothesized that inorganic fertilizer produces a higher grain yield over a single season, but manure application strongly improves soil quality.

Literature Review

There are areas of Africa (Fig. 3), were the soils have undergone such high levels of degradation that agricultural production has decreased during the past several decades, and the rate of soil nutrient loss in Africa is higher than in any other area of the world (Center for Soil Fertility and Agricultural Development, 2008). Problems in East and Central Africa are severe, specifically from high erosion, soil exhaustion from crops, and lack of fertilizer use. However, a Green Revolution may not be far away in Africa, as UN Millennium Villages, agricultural development project at the village level, are beginning to see drastic improvements in crop yields (Sanchez et al., 2009). Two important components to better land husbandry include: building SOM to improve soil moisture retention, nutrient supply, and soil structure; and integrating "plant nutrition management with locally appropriate, cost-effective combinations of organic/inorganic and on/off-farm sources of plant nutrients" (Pieri et al., 2002). In response to increasing levels of both soil degradation and food insecurity, it is critical that better resource management be implemented among African farmers. This includes securing nutrient sources for crop production and maximizing their efficiency. The objective of this project is to examine fertilizer and manure sources of N in an attempt to increase resource efficiency and improve food security.

Basic Concepts

Maize is classified as a tall-growing, monecious monocot cereal grain (Smith, 1995). Modern maize plants have one main culm containing 20 leaves. A plant typically has one, but occasionally more, lateral branch that bears an ear. Water availability is critical for maize production. Maize uses an increasing amount of water every day from about 30 days before silking until fertilization, when water uptake peaks at about 5 mm/day before steadily declining.

Therefore, maize is most susceptible to drought stress during the silking and early grain fill stages of its reproductive cycle. Rapid N, P, and K uptakes begin about 25 days after emergence, and by the silking, or flowering, stage, nutrient uptake is 50-60% complete (Smith, 1995).

Salasya et al. (1998) reports that KARI's general fertilizer recommendation for Western Kenya is 60 kg/ha N and 26 kg/ha P to accommodate low N and P levels in the area's soils. In the Kakamega District in Western Kenya, it is recommended to plant shortly after the onset of the rain season at depths between 2.5-5.0 cm to protect the seed against rodents and provide adequate moisture content. The recommended spacing for planting is 75 x 30 cm, resulting in a potential plant density of 44.4 thousand plants/ha. Maize is harvested when the leaves and husk are dry and the moisture content of the grain is less than 35%, best indicated by a black layer at the base of the kernel.

Nitrogen (N) is typically the nutrient of most concern due to its strong influence on cereal crop yields. It is most abundantly found in the N_2 gaseous form, 99.4% (Fig. 4) of which is found in the earth's atmosphere (Havlin et al., 2005). Plants take up N in the form of NH_4^+, a result of mineralization, and NO_3^-, a result of nitrification. Plants are one to six percent N by dry weight (Havelin et al., 2005). It is stored in the soil on the cation exchange complex (CEC) in the form of NH_4^+. In the forms of NO_3^- and NO_2^-, it has the potential to leach out of the root zone of the soil or undergo denitrification when it is lost to the atmosphere in the forms of N_2O, NO, and N_2.

Nutrient Management

Nutrients in the soil system may or may not be available to plants, or they may leave the soil system before plants utilize them. Therefore, proper nutrient management is a critical component to any crop production. Kihanda et al. (2006) observed a strong relationship between high rainfall and high crop yields, as water is needed to release nutrients to plant roots. In a study conducted by Kimetu et al. (2004), a very low grain yield was obtained during a season with poor rainfall distribution, again concluding that the optimal soil moisture regime is critical to production. This relationship was also shown in studies by Mucheru-Muna et al. (2007). However, water also contributes to nutrient leaching. When water percolation is high, N lost from leaching may also be high (Smith, 1995); this is most significant in sandy soils (van Es et al., 2006). Under prolonged anaerobic conditions, N can also be lost through denitrification (Smith, 1995). When N is applied to the soil surface, it may volatilize or be tied-up by microorganisms. van Es et al. (2006) reported that high quantities of residual N lead to high amounts of N leaching, specifically during times following dry growing seasons.

Treatment effects between various organic resources were observed within two weeks of emergence in a study by Mtambanengwe et al. (2006), showing the importance of N availability early in the growing season. This study indicated a strong correlation between an early, consistent supply of N and grain yield. Especially on sandy soils, maize accumulates less biomass and has lower grain yields when high quality organic fertilizers, or fast-N-releasing inorganic fertilizers, are unavailable. Salasya et al. (1998) also indicated the importance for P fertilizers. In the Kakamega District, it is recommended for all of the P and half of the N fertilizer be applied at the time of planting and for the remaining N fertilizer to be applied six weeks after plant germination, when the plants are approximately knee-high.

Soil carbon (C) also affects N availability. Soils surveyed by Makokha et al. (2001) in Kenya's Kiambu District were characterized by high levels (3-4%) of soil organic C (SOC), due to high levels of applied soil organic matter (SOM). High SOC concentrations can be correlated to high levels of N immobilization. For fertility purposes, a low C:N ratio (10-15) is ideal, because it allows N to be mineralized instead of immobilized by microbial organisms. Lekasi et al. (2002) conducted a study in the Central Kenya Highlands, examining the change in C:N ratio during organic manure composting. Results showed that when the C:N ratio with the compost decreased during decomposition, higher N concentrations were observed at the end of the composting period. Another study conducted by Kimetu et al. (2008) in Western Kenya indicated that organic matter (OM) with C:N ratios $\leqq$ 15 had a very short half life for decomposition; the OM decomposed rapidly by microorganisms, resulting in high levels of nutrient release.

Kapkiyai et al. (1999) studied maize yields and soil quality under different management strategies using combinations of inorganic fertilizer, cattle manure, and maize stover retention during an 18-year experiment. They showed that all management strategies decreased SOM over time, with the greatest loss from inorganic fertilization and stover removal; when manure was added and maize stover retained the rate of SOM depletion was less. Little significant differences were observed between treatments regarding total SOC in the soil, but particulate organic matter (POM) was greatly influenced by management and was a strong indicator of soil fertility, particularly N mineralization. A regression of SOC and crop yields indicated that every t C per hectare conserved through management resulted in an average maize yield increase of 243 kg per hectare per year. This relationship was the strongest with manure applications.

Inorganic Sources of Nitrogen

Czapar et al. (2007) recommend that if N fertilizers are applied in the fall, application should not occur until the soil temperature is < 10ºC (50ºF) and the fertilizer should be applied with a nitrification inhibitor to minimize nitrification. In a study conducted by Pilbeam et al. (1995), maize and beans were grown with fertilizer N rates ranging from 10 to 80 kg per hectare for the maize production. Results showed that dry matter production and grain yield were not affected by increases in N application. It was also calculated that the plants recovered less than 16% of the applied N from fertilizer, possibly because the N from fertilizer was diluted when soil organic N was quickly mineralized with the onset of the rainy season.

In a maize study conducted by Kimetu et al. (2006) on humic Nitisols of Central Kenya, 23% of the N applied through a urea split- application was lost through leaching down the soil profile (at 70-80 cm depth). This was observed during a growing season that received adequate rainfall. In a later experiment by Kimetu et al. (2008), inorganic fertilizer was applied to maize fields of varying levels of soil degradation, due to the number of years of continuous cultivation since deforestation. Results showed that both grain yield and total biomass production decreased by 66% during the first 35 years of cultivation and remained low despite inorganic fertilizer applications of the recommended levels for N, P, and K at rates of 120, 100, and 100 kg/ha, respectively. The study also showed that yields were higher on the sandier than on clayey soils.

Organic Sources of Nitrogen

In manure, between 50 and 75% of total N is organic ($R-NH_2$) and needs to undergo mineralization before it becomes available to plants. The remaining 25 to 50% is NH_4^+, which is highly susceptible to volatilization (Havlin et al., 2005). Ammonium-N (NH_4^+) is immobilized by bacteria upon the fertilizer's application to the soil surface. The degree of immobilization may increase by adding organic materials with a high C:N ratio compared with that of the manure (Thomsen, 2005). Increasing amounts of SOM within the soil provide more exchange sites on the CEC for N immobilization.

However, a study by Kimetu et al. (2008) showed that application of inorganic fertilizer together with 12 Mg of C per ha of wood charcoal, with a low N content and a high C:N ratio, produced maize yields that were about 2 Mg/ha higher than that from the inorganic application when the soil was highly degraded. This yield increase could not be explained by increasing nutrient availability, but possibly through improving soil pH, CEC, or soil moisture retention. A different study by Kimetu et al. (2004) concluded that the effects of using an organic source of N greatly depend on the quality of the organic source and its rate of decomposition. Organic fertilizers have the strong potential of increasing soil water retention, providing the soil with additional micronutrients, and possibly improving the soil's physical and chemical properties. A study in a semi-arid region of Ethiopia by Alemu and Bayu (2005) indicated that manure (average N = .42%) applied to sorghum (*Sorghum bicolor* L.) at rates of 10 and 15 Mg per hectare had the highest affect on increasing total soil N and C contents as well as available P, K, and Mg in comparison to lower rates of manure application. However, this study did not show manure to significantly improve soil pH, CEC, or base saturation.

Both C and N cycles are closely connected within the soil microbial community, and there exists a linear relationship between net C concentrations and N mineralization vs. immobilization (Mallory and Griffin, 2007). Kimetu et al. (2004) reported that organic C might help increase N mineralization from organic sources, thus expanding the N pool and increasing the amount of N available for crop production. Makokha et al. (2001) reported that the C:N ratio was high in cattle manure and low in swine and poultry manure. When examining organic fertilizers by N content, Mtambanengwe et al. (2006) observed the cattle manure to be of a medium quality in comparison to other organic materials. This study also indicated that when the organic material has a low N content, a low application rate leads to higher yields than a high application rate, due to the decreased time of N immobilization.

In conclusion, the addition of SOC through application of biosolids has the potential to increase crop yields by providing a high rate of N release and availability if the C:N ratio is low or if the OM improves the soil quality of a highly degraded system, such as increasing soil pH, CEC, and aggregation. In contrast, there is also the possibility that an increase in SOC concentration may decrease crop yield by increasing N immobilization by microorganisms.

Manure Management

Mineralization and N recycling begin as soon as the manure is incorporated into the soil. The rate of mineralization varies among N sources, but is the highest at application and decreases with time (Havlin et al., 2005). The risk of N volatilization increases with an increase in soil pH, is higher with surface application vs. when N is incorporated, and increases with increase in temperature and in the presence of crop residues. Volatilization may cause 15 to 40% loss of the total soil N. For these reasons, manure management needs to closely consider the effects of time and temperature on N availability, as well as the specific crop needs within these parameters (Crohn, 2006).

The N pool in manure declines during storage and handling (Ohio Livestock Manure Management Guide, 2006). Thus, proper management of manure is critical to minimize N loss. The consistency of the manure (liquid, slurry, semi-solid, or solid) must also be considered when developing a management plan. Solid manure storage allows for low nutrient loss, especially if the storage is covered. Slurry pits or tanks, below building pits, and earthen holding ponds have low to moderate nutrient loss. Treatment lagoons have high losses because of N volitalizaiton.

Sommer et al. (2007) reported that N mineralization during storage depends upon the reduction of SOM, as is observed by the production of CO_2 and CH_4 during storage. These reactions are in turn affected by temperature and the presence of an adapted microbial community in pre-stored manure slurry during the 100-200 day slurry incubation. Results showed that CH_4 production was not significant at temperatures < 15ºC but became significant at

20ºC, relative to CO_2 production. As a result, little N was mineralized during storage at 10ºC for both cattle and pig slurry as well as at 15ºC for cattle slurry. As much as 80% of organic N was mineralized at 15ºC for pig slurry and at 20ºC for cattle slurry. When manure was processed in an anaerobic digester for biogas production, there was no observable difference in maize yield between processed swine manure and raw swine manure (Loria et al., 2007).

Results from a study by Lekasi et al. (2002); in which combinations of cattle feces, urine, and rejected maize stover from feed were composted; showed that the addition of urine increased the compost's moisture content and N loss during storage. In regards to N availability for plant uptake, results showed that combinations that included rejected maize stover from feed produced high quality compost and higher N retention as compared to combinations lacking maize stover. It was hypothesized that compost not containing maize stover favored anaerobic decomposition.

Timing of application is a crucial component to maximizing N use efficiency. Organic fertilizers (e.g., manure) are harder to manage than mineral fertilizers, primarily because the former is affected by storage, handling, and time of incorporation and distribution timing (Thomsen, 2005). Maroko et al. (1998) reported a linear relationship between soil nitrate (NO_3-N) availability at the time of planting and maize yields. Autumn applications usually increase N loss through the soil system, in comparison with later applications, which leads to increases in crop utilization of N (Thomsen, 2005).

Leaching potential may change with different seasonal temperature regimes: late fall and spring applications, when soil temperatures are low, may have a different effect on N loss as compared to an early fall application (van Es et al., 2006). Other contributing factors affecting the rate of N loss include soil type, soil temperature and moisture regimes, crop uptake potential, and precipitation corresponding with percolation. In a study conducted by Loria et al. (2007), differences between maize yields among different site locations were attributed to N loss potential from a late fall application as opposed to a spring application at other sites.

Long Term Yield Effects of Manuring

It is widely documented that manuring has positive long-term effects on maize yield. Mucheru-Muna et al. (2007) conducted a seven-season study in Kenya, and reported that plots receiving a manure treatment had increase in pH, SOC concentration, and exchangeable Ca^{2+} and K^{+}. The increase in pH was attributed to the decrease in exchangeable Al^{3+} in the soils. Studies by Kihanda et al. (2006) showed that when manure was applied for seven consecutive years, crop yields increased and then stabilized. When manure was applied only for four consecutive years, yields remained high for seven or eight years before decreasing. These data indicated that a residual effect of manuring can sustain crop yields for at least seven years.

Mallory and Griffin (2007) conducted a long-term study to assess the effects of manure applications on soil characteristics and subsequent N availability from recently added N. Results showed that when no new N was added, net mineralization in soils with a history of organic management was twice that of soils with a history of industrial management. When N was added, results showed a strong interaction between the type of N added and the historical management of the soil. Soils that were historically organic-amended were characterized with larger soil C and N fractions, more readily available C and N pools, and more microbial biomass and activity than the control.

Comparison of Organic and Inorganic N Sources

A critical review of the available literature comparing organic and inorganic fertilizers indicates mixed results. Studies by Kihanda et al. (2004) reported that, over a seven-year period, Kenyan maize yields were similar in plots treated with goat manure to those receiving inorganic fertilizer. However, Mallory and Griffin (2007) observed that inorganic N applications became available quicker than N applications from manure. Mucheru-Muna et al. (2007) concluded that calliandra (*Calliandra calothyrsus*) was a low quality organic fertilizer because it had a high tendency to build SOM, creating a very slow release on N from mineralization.

Nziguheba et al. (2005) studied the effects of various organic treatments on biochemical properties, nutrient cycling, soil fertility, and crop yield. Results showed that the organic treatments improved several soil parameters, but there were only a few cases where the organic treatments had a greater effect than the inorganic treatments. This trend was primarily observed at higher rates of N mineralization and was dependent on the specific application rate of the inorganic fertilizer. It is hypothesized that, had the experiment lasted more than 2.5 years, results may have more conclusively indicated the potential advantages of organic over inorganic soil amendments. Okalebo et al. (1999) concluded that accumulations of residues from wheat (*Triticum aestivum*) straw or soybean (*Glycine max*) crop residue had positive effects on soil pH, C, N, and P concentrations.

Results from a study conducted by Kimetu et al. (2006) showed a higher level of N recovery in maize from urea applications as opposed to tithonia (*Tithonia diversifolia*) green manure, supposedly attributed to the readily available N in urea. There was also a higher level of N measured in the top 10cm of the soil profile at the end of the season in plots receiving urea application as opposed to tithonia, probably a result of the urea's split application as opposed to the one-time application of the tithonia. The lower recovery of N from tithonia was attributed to a possible lack of synchronization between N release from the green manure and plant uptake, and possible N retention within the organic N pool. Loss of N from tithonia was mainly due to volatilization of nitrous oxide (N_2O), attributed to the high levels of C and NO_3-N incorporated into the soil enhancing denitrification. Loss of N from urea primarily occurred through the soil profile from leaching, because of the below normal rainfalls during the season. Another study conducted by Kimetu et al. (2004) showed that maize biomass yields were higher from organic N sources than from urea during a season with inadequate rainfall. Grain yields were poor with all sources, but it was estimated that the organic N sources acted as mulch, thus increasing water retention in the soil and resulting in higher biomass yields in comparison to inorganic N sources.

Combining Organic and Inorganic N Sources

Synthesis of the available literature shows that the best solution is to combine inorganic and organic N sources. Mtambanengwe et al. (2006) observed that N availability from low quality organic materials can be improved with the application of an inorganic N fertilizer. Kapkiyai et al. (1999) reported that yields as well as SOC concentrations were the highest when both fertilizer and manure were applied along with retaining the maize stover on the field. However, the data were somewhat inconclusive because this treatment also had the highest rate of N application. Alemu and Bayu (2005) also concluded that there was an interaction affect when combining manure and inorganic fertilizer, but again results were somewhat inconclusive because the highest yields were obtained when the total rate of N application from both sources were the highest.

Okalebo et al. (1999) concluded that supplementing either wheat straw or soybean residues with inorganic fertilizer produced higher yields than through the inorganic application alone. However, it cannot be deciphered if this increase in yield was due to the organic amendments improving soil quality or was a reflection of adding the amount of N that was being applied per hectare. Kimetu et al. (2004) reported that, in season when rainfall was not a limiting factor, inorganic-organic combination was the best option for sustained yields. A combination of urea and tithonia produced a higher grain yield over three seasons than did either source independently. A similar trend was observed with application of senna (*Senna spectabilis*), but no significant difference was observed in the treatment involving a combination of urea and calliandra (*Calliandra spp.*). Without combining urea with an organic material, only tithonia was found to be a viable alternative to urea, with fertilizer equivalency ratings of 118 and 130%.

Mucheru-Muna et al. (2007) reported that maize yields were the highest from tithonia or from tithonia-mineral combined treatments. Tithonia, leucanena (*Leucanena leucocephala),* and calliandra all produced high yields when combined with a mineral N fertilizer. In contrast, manure based treatments produced lower yields. However, any treatment that included mineral N also decreased soil pH, attributed to the increase in available H^+ ions from the mineral fertilizer.

In another experiment, Kimetu et al. (2008) assessed the effects of different inorganic-organic combinations on continuous maize cultivation in Western Kenya on soils with varying degrees of degradation. An inorganic fertilizer treatment was used as the control with the variables being different types of additional organic materials. Cattle manure and *T. diversifolia* leaves were labile sources of SOC, and wood charcoal and sawdust were sources of stable OM. This study compared maize grain yields through increase in nutrient availability with that of increase in SOC concentration.

On sites where soils had been cultivated for less than five years after deforestation, no significant difference in grain yields were observed among treatments. However, on sites with severe soil degradation from a longer period of cultivation, the inorganic-organic combinations produced higher yields than the control involving inorganic fertilizer. There was also a direct relationship between the degree of degradation, or time of cultivation, and the amount of response from the added OM. The latter, giving labile C, performed much better than the stable C sources, indicating the importance of increasing nutrient availability over stable SOC as a means to improving crop yields. However, yield increases on the highly degraded sites from the inorganic-stable C combinations indicated that improving soil quality by increasing SOC concentration has a significant effect on increasing grain yields in highly degraded systems.

Materials

Study Area

The study area is located in the Kakamega District of Western Kenya (Fig. 5). The district's elevation lies between 1,250 and 2,000 m above sea level (m.a.s.l.) and covers an area of 1,395 km^2 (Mwale and Wambua, 2008). Temperatures average between 18-20.5ºC throughout most of the year, and mean rainfall averages 1200-2100 mm per year. The district experiences two yearly rainy seasons: the long rains, typically lasting from March until June, and the short rains from August through October. Kakamega is long-rain dependent, as the short rains are inadequate for maize production. The district's soil is dominated by Humic Nitisols (sub group Dystro-mollic Mitisol), classified as deep, red friable soils (Kenya Soil Survey, 2004). A Humic Nitisol is equivalent to a typic Palehumult by the USDA soil classification system (Kihanda et al., 1996). These soils are clayey and possess an argillic B-horizon (ISEM, 2007). Due to their highly weathered characteristics, these soils are slightly acidic and finely textured. The soils are non-saline, very deep, and possess a high capacity for water retention; but inherent fertility is low.

- *Site 1: Farm A*— This field was cultivated with napier, or elephant, grass (*Pennisetum purpureum*) during the last cropping season, and inorganic fertilizer had been applied.
- *Site 2: Farm B*— This field was cultivated with maize during the previous long rain season and sweet potatoes during the previous short rain season. No fertilizer had been applied.
- *Site 3: Farm C*— This field was cultivated with maize during the previous season, and no fertilizer had been applied.

- *Site 4: Farm D*— This field has only been under cultivation for five years. During the last cropping season, maize was grown during the long rain season and vegetables were grown during the short rain season, and inorganic fertilizer had been used.

N Sources

The inorganic fertlizer plots were treated with diammonium phosphate (DAP), nutrient content of 18-46-0, at the time of planting and calcium ammonium nitrate (CAN), nutrient content of 26-0-0, as a side-dress six weeks after emergence. Both fertilizers were applied at a rate of 120 kg/ha, allowing the plots to receive N at a rate of 5.28 g/m^2 (~53 kg/ha). The organic fertilizer plots were treated with cattle manure, which had been purchased to maintain consistency. The manure was analyzed for its nutrient content on a dry-weight basis at the Kenya Plant Health Inspector Services (KEPHIS) in Kitale, Kenya, located just north of the Kakamega District (Table 2). The manure was applied at a rate of 8 Mg/ha, allowing the plots to receive N at an average rate of 7.64 g/m^2 (~76 kg/ha).

Methods

Pre-planting:

- Five soil samples, each at two depths (0-15 cm and 15-30 cm), were collected from each farm site, and these samples were combined to form one 0-15 cm sample and one 15-30 cm sample for each site. Samples were dried and then analyzed at KEPHIS.
- One manure sample was taken from each of the two manure sources and analyzed at KEPHIS.

Planting: The layout (Fig. 6) will be replicated at each of the four farm sites. An additional control plot was located at Farm C.

- DAP was applied at a rate of 120 kg/ha to plots with the inorganic treatment. Fertilizer was applied manually to the seed hole and incorporated before the seed was added.
- Cattle manure was applied to the plots receiving the organic fertilizer treatment at a wet rate of 8 Mg/ha. The manure was applied using a hole-placement method, in which the manure is added to the soil with the seed. The manure was incorporated to a depth between 10 and 20 cm.
- Maize variety KSTP 94 was planted uniformly in all plots with a spacing of 30 by 75 cm.

Post Emergence:

- Plots were weeded and maintained as needed by the farmer in ownership of the land.
- Stand counts were determined for each plot by counting the total number of plants that have emerged from the middle two rows of each plot.
- Six weeks after emergence CAN was applied at a rate of 120 kg/ha to all the plots receiving the inorganic fertilizer treatment. The CAN fertilizer was applied manually in a rill about 10 cm deep and 10 cm away from the maize rows.

R1 Stage:

- Plant height was measured for 10 plants from the inner two rows of each plot by using a meter stick to measure the distance from the ground at the base of the plant to the collar of the ear leaf. The average plant height for each plot was calculated for statistical analysis.
- A leaf color chart (a general indicator of the N content within the plant) was used to measure the color of the ear leaf for 10 separate plants from the inner two rows of each plot to the nearest half unit (Fig. 7). The average color measurement for each plot was calculated for statistical analysis.
- 10 ear leaves were sampled from the inner two rows of each plot. The leaves were dried and ground, without their collars, in an electric grinder, creating one homogenous sample from each plot. Samples were analyzed in the soil chemical lab at The Ohio State University, Columbus.
- 5 soil samples were collected from each plot, each at two depths (0-15 cm and 15-30 cm). Samples were combined to form one 0-15 cm sample and one 15-30 cm sample for each plot. Samples were air dried and analyzed in the soil physics lab and the soil chemistry lab at OSU.

Harvest:

- Stand counts were determined again for each plot by counting the total number of plants, with or without an ear, from the middle two rows of each plot.
- 3 soil samples were collected from each plot, each at two depths: 0-15 cm and 15-30 cm (Fig. 8). Samples were combined to form one 0-15 cm sample and one 15-30 cm

sample for each plot. Samples will be air-dried in the shade, and then analyzed at the soil chemistry lab at OSU.

- Ears were harvested from the middle section of the middle two rows of each plot, and the maize was shelled and weighed in the field. A moisture meter was used to determine the average moisture content from each plot, and the yields were converted to a moisture content of 14%. The number of plants harvested was counted and compared to the stand counts to calculate the area harvested.
- Fresh plant biomass was determined by bundling and weighing the plants harvested from each plot without the husks or ears (Fig. 9).
- Bulk density was measured in each plot by creating a smooth surface area in the field sampling to a depth of 5 cm with a .75 inch diameter soil probe. Soils cores were dried in an oven at 105º C for two days, and bulk density was calculated by the gravimetric method.

Laboratory Analysis:

Soil samples from the R1 stage and harvest stage were analyzed together in the soil chemistry and soil physics laboratories at OSU in Columbus, OH. Soil samples were prepared for analysis by crushing the samples using a mortar and pestle. Soil pH was measured in a 1:1 soil:deionized water suspension using a combination pH electrode (Thomas, 2001). Total N and total C were measured in the soil samples by the dry combustion following acid pretreatment (Nelson and Sommers, 2001). Total CEC in the soil was measured using an unbuffered ($BaCl_2$) salt extraction method (Sumner and Miller, 2001). Plant available nutrients in the soil were measured using the Mehlich 3 extraction with subsequent analysis by ICP-AES (Mehlich, 1984). Sub-samples from each 0-15 cm soil sample were combined to form one sample per treatment per farm site per sampling time to determine the percentage of water stable aggregates by wet sieving (Fig. 10).

Ear leaf tissue samples were prepared by running the samples through a grinder. Total N and total C were measured in the tissue samples by the dry combustion following acid pretreatment (Nelson and Sommers, 2001). Tissue samples were analyzed for nutrient content by adding 1 mL hydrochloric acid and 5 mL nitric acid to each .5 g tissue sample and leaving the samples underneath a laboratory hood overnight. Samples were then heated on a hot plate where the temperature remained over 100ºC for 30 minutes. Deionized water was then added to each sample until the volume equaled 25 mL at room temperature. The samples were then filtered and the solutions were analyzed using an ICP-AES.

Statistical Analysis:

JMP 7 statistical software was used to conduct an analysis of variance and combined analysis of variance will be conducted using ANOVA to compare treatment means within each site and between all four sites.

Results and Discussion

Organic vs. inorganic sources of nutrients

The inorganic fertilizer produced an average grain yield of 3.95 Mg/ha in comparison with that of 2.35 Mg/ha produced from the organic cattle manure (different at .05%). These yields indicate a difference of 68% in favor of the inorganic fertilizer. This trend in crop yield is also supported by the analyses. There were no differences in soil nutrient concentrations to a depth of 15 cm during either of the sampling times (Appendix III). However, treatment differences were observed in the maize ear leaf nutrient contents. The inorganic fertilizer treatment resulted in higher levels of N, P, Ca, Mg, S, and Zn within the maize ear leaf than those in the treatment receiving organic manure (significant to .05%) (Table 1).

The total N content in the leaves was 50% higher from the inorganic fertilizer than from the manure. Phosphorus, a limiting soil nutrient in Western Kenya, was 28.9% higher in the ear leaf from the inorganic fertilizer than that from the manure treatment. Although soil nutrients levels were not significantly different among treatments, plant nutrient levels were (Table 1).

Table 1. Treatment effect on ear leaf nutrients at R1, $\alpha = .05$

Trt.	N		P		K		Ca		Mg		S		Fe		Zn	
	g/kg												mg/kg			
F	22.8	a	2.22	a	18.40	a	5.17	a	1.67	a	1.54	a	336.00	a	18.97	a
M	15.2	b	1.73	b	19.63	a	3.77	b	1.28	b	1.33	b	389.67	a	16.84	b
CL	30.0		2.5		19.0		4.0		2.5		—		15.0		17.2	

CL = Critical Level for ear leaf at tassel (data taken from Jones et al., 1995).

Trends in the nutrient concentration in maize leaves show that the necessary nutrients for plant growth, and ultimately reflected in grain yields, are more readily available to the plants from an inorganic than organic source (Mallory and Griffin, 2007). However, had the study been extended over several growing seasons, there would potentially be an insignificant difference between inorganic fertilizer and manure (Nziguheba et al., 2005), as was shown during a seven-year study by Kihanda et al. (2004). Manure may have also performed better than the inorganic fertilizer if rainfall had not been adequate (Kimetu et al., 2004). The rainfall received during the growing season was adequate (Appendix VII).

No soil quality advantages were observed as a result of the manure treatment. The lack of difference in soil quality may be because of the short duration of a single-season study. Organic sources often do not show soil quality advantages over inorganic fertilizers during a short-term time frame (Nziguheba et al., 2005). It is also possible that the application rate of manure was not high enough to compensate the degradation of the soil by cultivation.

Crop yields

Although both farms and treatments produced higher yields than Kenya's national average, experimentally measured yields in this study were low. The threshold level of nutrient concentration in ear leaves at silking and tasseling stages is 29-30 g/kg N, below which deficiency symptoms are apparent and adversely impact crop growth (Jones et al., 1995). Application of manure resulted in an average N content within the maize ear leaf at silking of 15.2 g/kg, compared with 22.8 g/kg from inorganic fertilizer. Nutrient removal rates estimated from maize grain and stover yields (NRCS, 2008) were used to calculate the quantity of nutrients harvested through maize production (Table 2). These estimates may be slightly high, as nutrient concentrations found during this experiment were below the critical levels. Nonetheless, the data shows that more N is leaving the field every year than is being applied. The nutrient deficit can be reduced if crop residue is left on the field, but some will still be lost to volatilization, leaching, and immobilization. For these reasons, the current N recommendation rate in Western Kenya of 50 kg N per hectare is too low to obtain a high yield.

Similarly, the critical level for P in the maize ear leaf at tassel is 2.5 g/kg (Jones et al., 1995). Ear leaf concentrations of P were also below the critical level (Table 1). The fertilizer treatment produced P levels of 2.22 g/kg compared with that in manure of 1.73 g/kg. Therefore, maize crop also suffered from deficiency of P. In contrast to leaf concentrations of N and P, levels of K were near the critical limit for both treatments. Concerning Ca, only the fertilizer treatment produced an average concentration above the critical value. Concentrations of Mg were below the critical level for both treatments, and Zn concentrations were sufficient for the fertilizer treatment and near the critical limit for the manure treatment (Table 1).

Table 2. Nutrient Removal from Maize Grain and Stover

Location	Treatment	Yield (Mg/ha, 0% Moisture)	Grain or Stover	N Removed	P Removed	K Removed
				----------------------	kg/ha	----------------------
Farm C	Fertilizer	3.17	Grain	52.1	10.1	10.9
			Stover	31.2	3.2	47.7
			Total	**83.2**	**13.2**	**58.6**
Farm C	Manure	2.25	Grain	37.00	7.1	7.7
			Stover	22.1	2.3	33.9
			Total	**59.1**	**9.4**	**41.6**
Farm D	Fertilizer	3.75	Grain	61.6	11.9	12.9
			Stover	36.9	3.8	56.4
			Total	**98.5**	**15.6**	**69.3**
Farm D	Manure	1.88	Grain	30.9	6.0	6.5
			Stover	18.5	1.9	28.3
			Total	**49.4**	**7.8**	**34.8**

**Nutrient Removal Rates taken from NRCS (2008); Stover and grain yields were assumed equal*

Concentrations of Fe were at toxic levels for both treatments, with no statistical difference between treatments. Jones et al. (1995) sites literature regarding the upper limit of the sufficiency range for Fe in the maize ear leaf at tassel as 120 and 250 mg/kg. The author explains that these may be only general estimates for the upper limit, as less research has been done to identify them. Regardless, iron concentrations for this experiment averaged 336 mg/kg from the fertilizer treatment and 390 mg/kg from the manure treatment—far beyond the toxic limit.

Soil acidity, high Fe levels in the soil, and toxic Fe concentrations in the plants probably significantly hindered grain yields. At 15 cm depth at harvest, average pH levels ranged from 5.4 at Farm C to 4.8 at Farm A (Table 3). At both sampling times and depths, there were no significant differences among soil P levels, which is known to be deficient in Western Kenya. This deficiency is primarily a result of low soil pH levels, resulting in toxic Fe concentrations within the soil that bind to P, preventing it from becoming available. A regression analysis showed a negative correlation between soil pH and soil Fe levels, with a R^2 value of .56. Regression equations also showed a negative correlation between soil Fe and soil P levels, and positive correlations were calculated between both soil pH and soil P levels with grain yields. However, the R^2 values for these equations were only .09, .04, and .11 respectfully, due to the small sample numbers.

Table 3. Soil pH at site at two depths at R1 and Harvest samplings

Location	15 cm R1		30 cm R1		15 cm H		30 cm H	
Farm A	4.8	b	4.8	b	4.8	c	4.6	b
Farm B	5.7	a	5.5	a	—	—	5.6	a
Farm C	5.6	a	5.5	a	5.4	a	5.6	a
Farm D	—	—	—	—	5.0	b	4.8	b

It is probable that soil degradation had a significant effect on nutrient availability in the soil and consequently final grain yields. Although there were no statistically significant differences between treatments concerning nutrient levels within the soil, there were many location effects at both sampling depths. The highest amounts of total N, total C, Ca, and Mg were all observed at Farm D (Table 4).

Table 4. Soil nutrients in top 15 cm at Harvest

Location	Total N (g/kg)		Total C (g/kg)		Ca (mg/kg)		Mg (mg/kg)	
Farm A	0.58	b	9.60	b	329.87	b	29.06	b
Farm C	0.45	c	6.87	c	691.64	a	79.94	a
Farm D	1.34	a	20.72	a	879.12	a	106.77	a

Farm D has only been under cultivation for the past five years, whereas the other three sites have been under long-term cultivation (Fig. 1). The high degree of soil quality at this site is obvious by the lowest soil bulk density (Appendix VI), and the highest mean weight diameter (MWD), as calculated from its percentage water stable aggregates (WSA) (Table 4). Among the fertilizer treatments, the MWD from Farm D at harvest was 244% higher than that at Farm A and C and 625% greater than the MWD at Farm B. Among the manure treatments at harvest, the MWD at Farm D was 299% high than that at Farm A, and 273% higher than that at Farm C. These trends indicate a strong correlation between soil quality and grain yields.

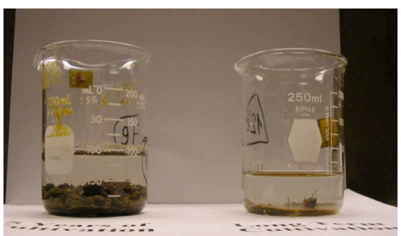
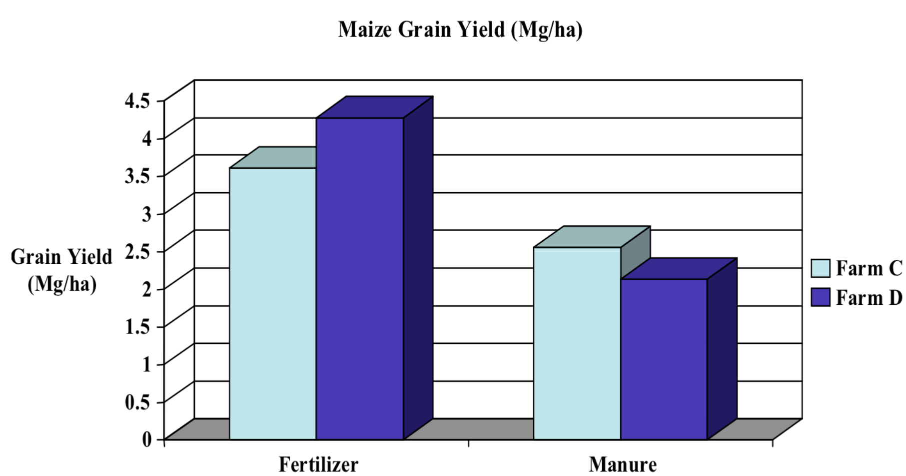


Fig. 1. 4.75 mm samples from WSA analysis.
Left: Farm D (5 years of cultivation)
Right: Farm A (long-term cultivation)

Table 4. Percentage of water stable aggregates and mean weight diameter at Harvest

	Fertilizer Treatment		Manure Treatment	
Location	WSA (%)	MWD (mm)	WSA (%)	MWD (mm)
Farm A	75.5	1.20	72.2	0.91
Farm B	65.4	0.57	—	—
Farm C	72.8	1.20	70.5	1.15
Farm D	87.8	**4.13**	83.6	**3.63**

Fig. 2. Treatment difference is greater at Farm D than at Farm C.



The differences between treatments were much greater at Farm D, which has been under cultivation for five years, than at Farm C, which has been under long-term cultivation (Fig. 2). The data in Figure 2 indicate a correlation between soil quality and the effectiveness of the inorganic fertilizer. This conclusion was also reached by Kimetu et al. (2008) whose study showed that maize yields would remain low on fields that have been cultivated for more than 35 years despite full inorganic fertilizer applications. The study extended to show that this yield decline could be reversed by adding organic amendments to the soil in addition to the inorganic fertilizer application.

Poor maize stands may have also contributed to low yields. The seeding rate used in this experiment was 44.4 thousand seeds per ha. Final plant stands, as calculated at harvest, ranged from 29.5 thousand plants per ha to 45.7 thousand plants per ha. There was as high as a 33.6% decrease in plant populations in comparison to its seeding rate.

Table 5. Plant stand at harvest (plants/ha)

Farm Site	Plot #	Treatment	Harvest Stand from Inner 2 Rows	Calculated Plants per Hectare (1000)
Farm C	1	Fertilizer	31	29.5
Farm C	2	Manure	41	39.0
Farm C	3	Fertilizer	47	44.8
Farm C	4	Manure	38	36.2
Farm C	5	Fertilizer	33	31.4
Farm C	6	Manure	39	37.1
Farm D	1	Fertilizer	39	37.1
Farm D	2	Manure	36	34.3
Farm D	3	Fertilizer	41	39.0
Farm D	4	Manure	39	37.1
Farm D	5	Fertilizer	35	33.3
Farm D	6	Manure	33	31.4

Research Errors and Future Studies

There was a lot of error in this study due to its small scale. Many times the data had to be transformed before it could be statistically analyzed because there were often not enough samples for the data to be normally distributed. There was also only one control plot for the entire experiment, so there was no way to compare it statistically with the two treatments. Future studies need to have the control plot replicated as many times as each treatment is replicated for a correct analysis, and ideally it should have a greater total number of samples, either through additional treatments or replications, in order to create a better assessment.

There was also error due to the author's inexperience and that of the Kenyan researchers and farmers who were assisting. Yield data were only collected from two of the four experimental locations due to poor communication and understanding from the farmers. Due to my inexperience in research methods, the experiment was not properly designed to include replicated control plots, and I failed to be familiar enough with sampling techniques before collecting the field data at harvest. This resulted in an incorrect measurement of aboveground biomass due to inaccurate measurements of the plant moisture content at the time of harvest. As a result of poor foresight and communication with the research technicians, the area harvested from each plot was not measured or consistent; consequently stand counts had to be used to estimate the area harvested.

Future research should include developing nutrient response curves, especially for N, for maize production in the tropics. This experiment showed that the current recommended rate of 50 kg N per ha is not enough to reach the critical level required for maize to produce high yields. Other studies have focused on comparing different combinations of N additives, but these studies fail to maintain the same total N input within the experimental framework. Consequently, the effects of different N sources are masked by the amount of N each treatment is receiving. The end results typically show that the highest yields are attained when the most N is applied. Future studies must be designed to compare the yield effect from both total N rate and different sources of N. This study also showed that the greatest treatment difference was observed at Farm D, which had the lowest degree of soil degradation. Future studies should explore this relationship further to determine if and where thresholds exist that would alter recommendations concerning the rate and source of N.

Conclusion

Under the parameters of this study, inorganic fertilizer produced maize yields 68% greater than did cattle manure, even though N rates were equal. Tissue analysis of the maize ear leaves showed significantly higher levels of N, P, Ca, Mg, S, and Zn from the inorganic than organic treatment. These higher nutrient levels corresponded to higher yields. However, yields were still low, and most of the nutrients in the plant tissue were below the critical nutrient levels. Further, it was estimated that up to twice the amount of N was leaving the field via the grain and plant biomass than was applied in the form of fertilizer and manure. For these reasons, it can be concluded that the recommended rate of 50 kg N per ha is not enough. This is especially true if the soil is to be replenished of the nutrients lost from long-term cultivation and soil degradation.

There is also a potential correlation between the level of soil degradation and the extent to which fertilizer out-performed the organic manure. At the farm site where the soil was considerably less degraded, the significance between treatments was much greater than at the site with degraded soil. This shows the importance of soil quality and SOM as they affect soil fertility. The soil may not be able to take full advantage of fertilizer rates if the soil is degraded. In order for the soils provide the necessary nutrients for plant production, management should focus on building up the OM content of the soils to increase soil quality. Applying manure and other sources of OM is the most common method for this.

Because farmers do not usually have the economic means to apply high rates of fertilizer to all of their fields, farmers should consider the economic costs and benefits from concentrating their nutrient resources on one specific site for maize production, and possibly grow a crop that is less nutrient demanding on remaining land. Unless nutrient resources are concentrated, the soil will continue to degrade and available nutrients in the soil will continue to be depleted.

Tables and Figures

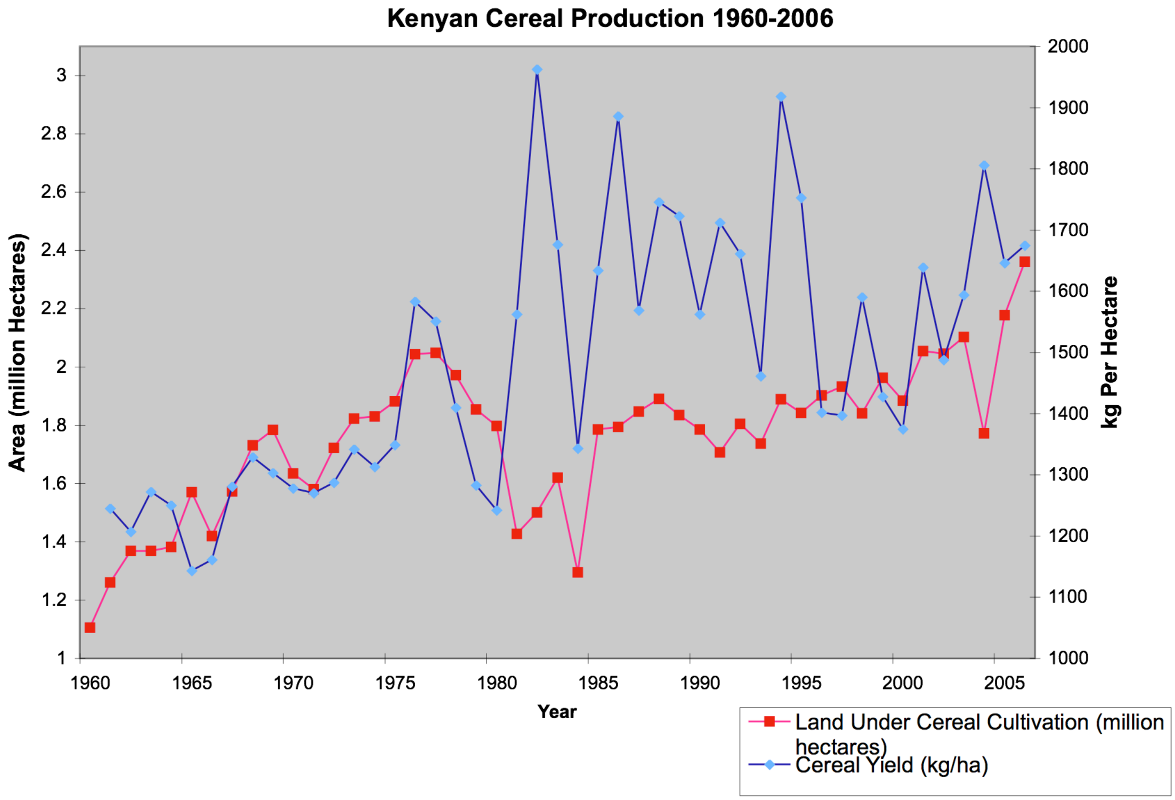


Fig. 1 Kenya Cereal Production 1960-2006 (created from World Bank, 2007).

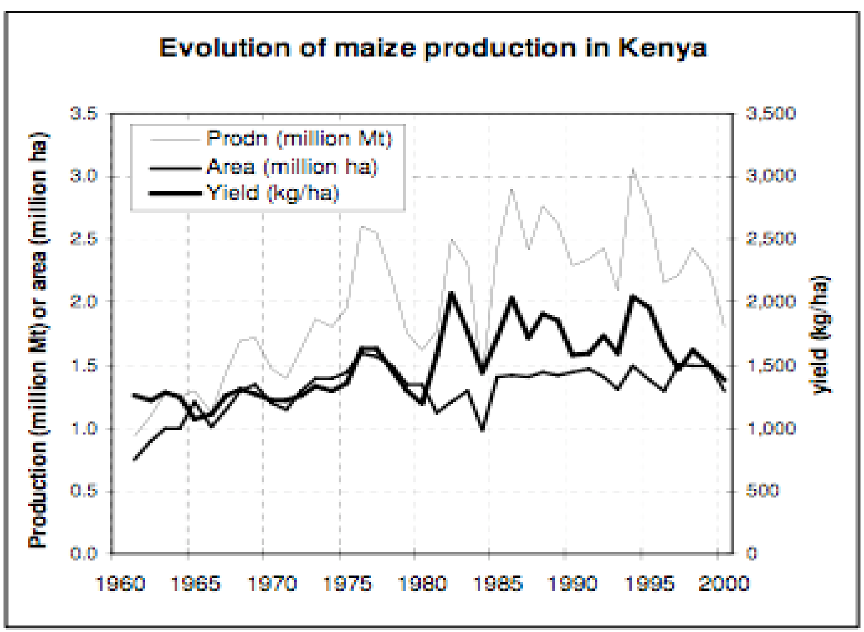


Fig. 2. Evolution of maize production in Kenya (Groote et al., 2005).

1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
33	63	51	53	54.2	69.9	80	62.7	118.5	74.6	38.9

Table 1. Kenya's yearly N fertilizer consumption from 1995-2005, thousand metric tons (*United Nations Statistical Division, 2008)*

Figure 3. Shaded areas show where current population exceeds agricultural capacity. (International Center for Soil Fertility and Agricultural Development).

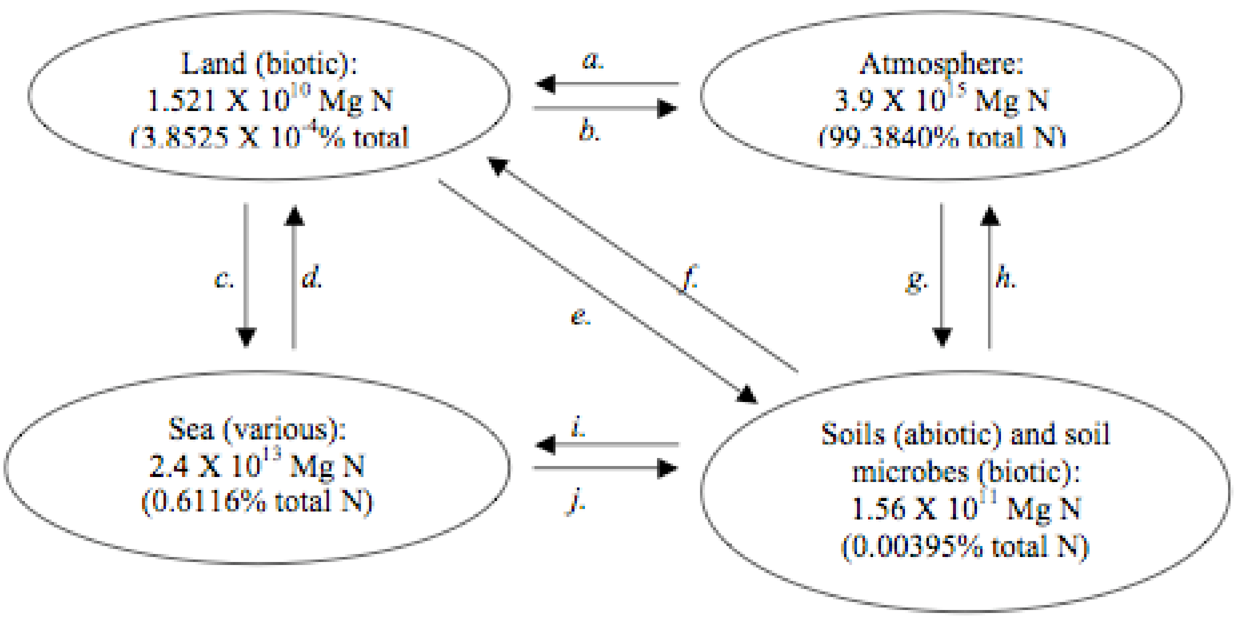


Fig. 4. N-cycle schematic through the biomes. a. biological N fixation. b. denitrification. c. runoff. d. deposits. e. decomposition of organic matter. f. N-uptake by plants. g. electrical, combustion, and industrial processes. h. volatilization of nitrious oxides. i. nutrient leaching through soil profile. f. deposits. (created from Havlin et al., 2005).

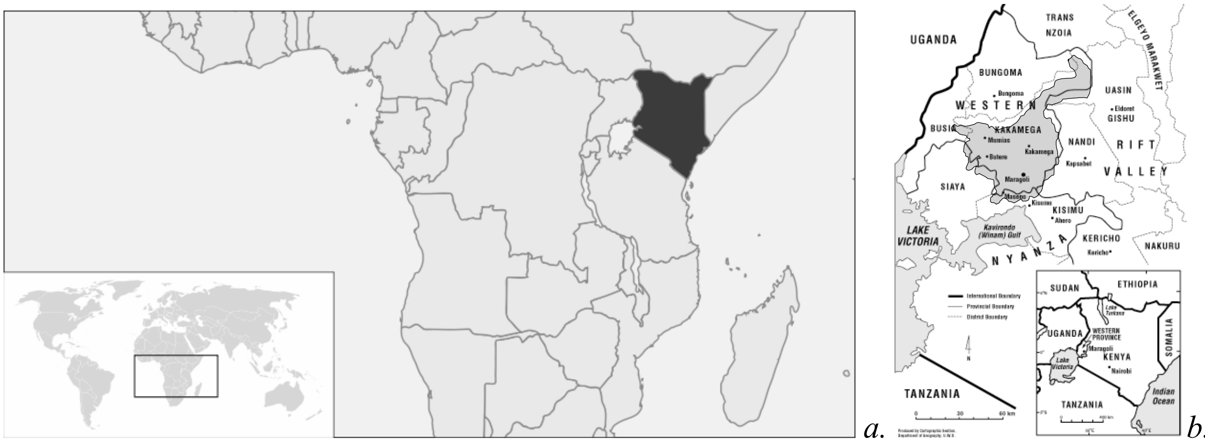


Fig. 5. a. Kenya is located in East Africa, extending both north and south of the equator (Wikipedia, 2008). b. The Kakamega District is located in Western Kenya (International Development Research Center, 2001).

	Farm Yard Manure 1	Farm Yard Manure 2
pH	7.09	7.62
Potassium (%K)	0.85	0.36
Sodium (%Na)	0.40	0.40
Calcium (%Ca)	2.25	0.16
Magnesium (%Mg)	0.23	0.16
Phosphorus (%P_2O_5)	7.81	6.57
Nitrogen (%N)	0.92	0.99
Manganese (Mn ppm)	6314.35	6485.66
Copper (Cu ppm)	3389.57	4704.71
Zinc (Zn ppm)	2423.79	3369.68

Table 2. Manure Test Report from Kenya Plant Health Inspectorate Service (KEPHIS) Kitale Office.

4 rows of maize; 3 x 7 meters; N from DAP, CAN	4 rows of maize; 3 x 7 meters; N from cattle manure
bare area separating plots	
4 rows of maize; 3 x 7 meters; N from cattle manure	4 rows of maize; 3 x 7 meters; N from DAP, CAN
bare area separating plots	
4 rows of maize; 3 x 7 meters; N from DAP, CAN	4 rows of maize; 3 x 7 meters; N from cattle manure

Fig. 6. Aerial layout of plot plan, replicated at four locations.

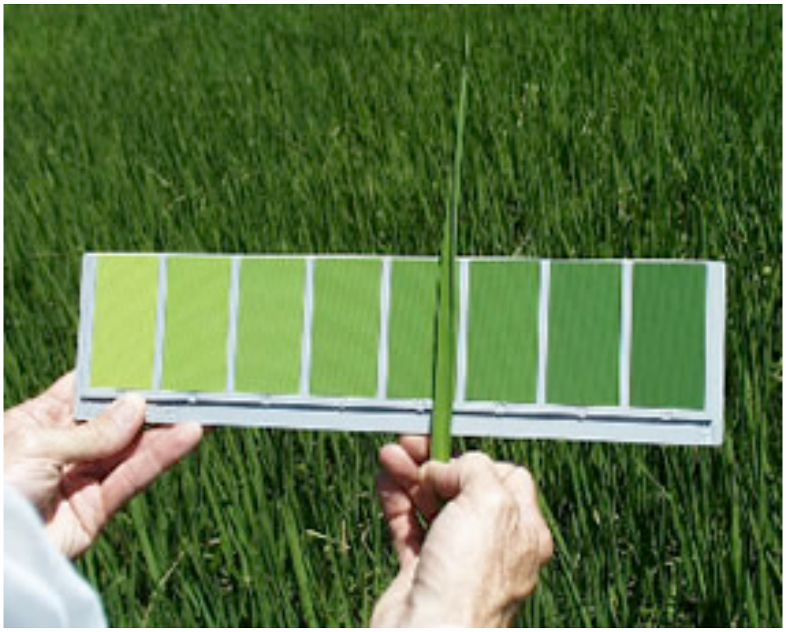


Fig. 7. Leaf Color Chart, giving a scale rage of 1-8 (University of California Delivers).

Fig. 8. Harvest soil sampling at Farm B.

Top photo: 0-15 cm sample

Left photo: 15-30 cm sample

Fig. 9. Weighing harvested biomass at Farm C.

Fig. 10. Wet Sieving

Top Left: Harvest Soil Samples (From L to R: Field A, B, C, D)

Top: Sample Soaking 30 min

Left: Samples Sieving 30 min

Literature Cited

Alemu, G., and W. Bayu. 2005. Effects of farmyard manure and combined N and P fertilizer on sorghum and soil characteristics in Northeastern Ethiopia. J. Sustain. Agr. 26(2):23-40.

Crohn, D.M. 2006. Optimizing Organic fertilizer applications under steady-state conditions. J. Environ. Qual. 35:658-669.

Czapar, G.F., J. Payne, and J. Tate. 2007. An education program on the proper timing of fall-applied nitrogen fertilizer. Plant Management Network.

van Es, H.M., J.M. Sogbedji, R.R. Schindelbeck. 2006. Effect of manure application timing, crop, and soil type on nitrate leaching. J. Environ. Qual. 35:670-679.

Export Processing Zones Authority. 2005. Grain Production in Kenya: 2005. Export Processing Zones Authority. Nairobi, Kenya.

Groote, H.D., G. Owuor, C. Doss, J. Ouma, L. Muhammad, and K. Danda. 2005. The maize green revolution in Kenya revisited. *e*-J. Agr. Devel. Econ. 2:32-49. Available at http://www.fao.org/es/esa/eJADE (accessed 17 April 2008).

Havlin, J.L., S.L. Tisdale, W.L. Nelson, and J.D. Beaton. 2005. Nitrogen. p. 97-159. *In* Soil Fertility and Fertilizers: An Introduction to Nutrient Management. Pearson Education, Inc., Upper Saddle River, New Jersey.

International Center for Soil Fertility and Agricultural Development. 2006. Africa Soil Exhaustion. Science 312:31.

International Development Research Centre (IDRC). 2001. Western Province and Kenya, East Africa [Map]. Available at http://archive.idrc.ca/books/focus/929/CHAPTER3.HTML (accessed 11 April 2008).

International Society for Ecological Modeling (ISEM). 2007. FAO - Soil Unit Classification Scheme: Nitisols. Available at http://eco.wiz.uni-kassel.de/ecobas/help_docs/nitisols.html (accessed 31 December 2007).

Jones, J.B.Jr., H.V. Eck, and R. Voss. 1995. Plant Analysis as an Aid in Fertilizing Corn and Grain Sorghum. p. 521-547. *In* Soil Testing and Plant Analysis. 3rd ed. SSSA. Madison, Wisconsin.

Kapkiyai, J.J., N.K. Karanja, J.N. Qureshi, P.C. Smithson, P.L. Woomer. 1999. Soil organic matter and nutrient dynamics in a Kenyan nitisol under long-term and organic input management. Soil Biol. Biochem. 31:1773-1782.

Kenya Soil Survey. 2004. Gateway to Land and Water Information. Available at http://www.fao.org/ag/agl/swlwpnr/reports/y_sf/z_ke/ke.htm (published 29 July 2004, accessed 31 December 2007). Food and Agriculture Organization of the United Nations.

Kihanda, F.M., G.P. Warren, and A.N. Micheni. 2006. Effect of manure application on crop yield and soil chemical properties in a long-term field trial of semi-arid Kenya. Nutr. Cycl. Agroecosyst. 76:341-354.

Kihanda, F.M., M. Wood, M.K. O'Neill, and A.F.E. Palmer. 1996. Fertilizer nitrogen recovery efficiency in the sub-humid highlands of Central Kenya. *In* Edmeades et al. (ed). Developing Drought- and Low N- Tolerant Maize, El Batán, Mexico. 25-29 March 1996. CIMYT.

Kimetu, J.M., D.N. Mugendi, C.A. Palm, P.K. Mutuo, C.N. Gachengo, A. Bationo, S. Nandwa, and J.B. Kungu. 2004. Nitrogen fertilizer equivalencies of organics of differing quality and optimum combination with inorganic nitrogen sources in Central Kenya. Nutr. Cycl. Agroecosyst. 68:127-135.

Kimetu, J.M., D.N. Mugendi, A. Bationo, C.A. Palm, P.K. Mutuo, J. Kihara, S. Nandwa, and K. Giller. 2006. Partial balance of nitrogen in a maize cropping system in humic nitisol of Central Kenya. Nutr. Cycl. Agroecosyst. 76:261-270.

Kimetu, J.M., J. Lehmann, S.O. Ngoze, D.N. Mugendi, J.M. Kinyangi, S. Riga, L. Verchot, J.W. Recha, and A.N. Pell. 2008. Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. Ecosystems 11:726-739.

Lal, R. 2009. Laws of sustainable soil management. Agron. Sustain. Dev. 29:7-9.

Lal, R. 2009. Soils and food sufficiency. A review. Agron. Sustain. Dev. 29:113-133.

Lal, R. 2008. Soils and sustainable agriculture. A review. Agron. Sustain. Dev. 28:57-64.

Lekasi, J.K., J.C. Tanner, S.K. Kimani, and P.J.C. Harris. 2002. Manure management methods to enhance nutrient quantity and quality on smallholdings in the Central Kenyan Highlands. Biol. Agric. Hortic. 19:315-332.

Loria, E.R., J.E. Sawyer, D.W. Barker, J.P. Lundvall, and J.C. Lorimor. 2007. Use of anaerobically digested swine manure as a nitrogen source in corn production. Agron. J. 99:1119-1129.

Makokha, S., S. Kimani, W. Mwangi, H. Verkuijl, and F. Musembi. 2001. Determinants of fertilizer and manure use for maize production in Kiambu District, Kenya. International Maize and Wheat Improvement Center (CIMMYT), Mexico.

Mallory, E.B., and T.S. Griffin. 2007. Impacts of soil amendment history on nitrogen availability from manure and fertilizer. Soil Sci. Soc. Am. J. 71:964-973.

Maroko, J.B., R.J. Buresh, and P.C. Smithson. 1998. Soil nitrogen availability as affected by fallow-maize systems on two soils in Kenya. Biol. Fertil. Soils 26:229-234.

Mehlich, A. 1984. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Comm. Soil Sci. Plant An. 15:1409-1416.

Mtambanengwe, F., P. Mapfumo, and B. Vanlauwe. 2006. Comparative short-term effects of different quality organic resources on maize productivity under two different environments in Zimbabwe. Nutr. Cycl. Agroecosyst. 76:271-284.

Mucheru-Muna, M, D. Mugendi, J. Kung'u, J. Mugwe, and A. Bationo. 2007. Effects of organic and mineral fertilizer inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya. Agroforest Syst. 69:189-197.

Mwale, M., and H. Wambua. 2008. Kakamega District Food Security Rapid Assessment Report February 2008.

NRCS. 2008. Plant Nutrient Content Database. Available at http://www.nrcs.usda.gov/technical/ecs/nutrient/tbb1.html (accessed 22 May 2009).

Nelson, D.W., and L.E. Sommers. 2001. Total Carbon, Organic Carbon, and Organic Matter. p. 961-1010. *In* Methods of Soil Analysis, Part 3—Chemical Methods. SSSA. Madison, Wisconsin.

Nziguheba, G., R. Merckx, and C.A. Palm. 2005. Carbon and nitrogen dynamics in a phosphorus-deficient soil amended with organic residues and fertilizers in western Kenya. Biol. Fertil. Soils 41:240-248.

Ohio Livestock Manure Management Guide. 2007. Bulletin 604. The Ohio State University, Columbus, OH.

Okalebo, J.R., C.A. Palm, M. Gichuru, J.O. Owuor, C.O. Othieno, A. Munyampundu, R.M. Muasya, and P.L. Woomer. 1999. Use of wheat straw, soybean trash and nitrogen fertilizer for maize production in the Kenyan highlands. Afr. Crop Sci. J. 7:423-431.

Pilbeam, C.J., M. Wood, and P.G. Mugane. 1995. Nitrogen use in maize-grain legume cropping systems in semi-arid Kenya. Biol. Fertil. Soils 20:57-62.

Salasya, B.D.S., W. Mwangi, H. Verkuijl, M.A. Odendo, and J. Odenya. 1998. An assessment of the adoption of seed and fertilizer packages and the role of credit in smallholder maize production in Kakamega and Vihiga Districts, Kenya. International Maize and Wheat Improvement Center (CIMMYT), Mexico.

Sanchez, P.A., G.L. Denning, and G. Nziguheba. 2009. The African Green Revolution moves forward. Food Sec. 1:37-44.

Smith, W.C. 1995. Corn (Zea mays *L.*) p. 1-56. *In* Crop Production: Evolution, History, and Technology. John Wiley & Sons, Inc., New York.

Sommer, S.G., S.O. Petersen, P. Sørensen, H.D. Poulsen, and H.B. Møller. 2007. Methane and carbon dioxide emissions and nitrogen turnover during liquid manure storage. Nutr. Cycl. Agroecosyst. 78:27-36.

Sunmer, M.E., and W.P. Miller. 2001. Cation Exchange Capacity and Exchange Coefficients. p. 1201-1229. *In* Methods of Soil Analysis, Part 3—Chemical Methods. SSSA. Madison, Wisconsin.

The World Bank Group, 2007. WDI Online. Available at http://ddp-ext.worldbank.org.proxy.lib.ohio-state.edu/ext/DDPQQ/member.do?method=getMembers&userid=1&queryId=6 (accessed 31 December 2007 and 6 April 2009).

Thomas, G.W. 2001. Soil pH and Soil Acidity. p. 475-490. *In* Methods of Soil Analysis, Part 3—Chemical Methods. SSSA. Madison, Wisconsin.

Thomsen, I.K. 2005. Crop N utilization and leaching losses as affected by time and method of application of farmyard manure. Europ. J. Agron. 22:1-9.

United Nations. 2008. Millennium Development Goals: Progress Report. Available at http://www.undp.org/publications/MDG_Report_2008_En.pdf (accessed 3 April 2009).

United Nations Economic and Social Affairs. 2004. World Population to 2300. Available at http://www.un.org/esa/population/publications/longrange2/WorldPop2300final.pdf (accessed 6 April, 2009).

United Nations Statistics Division. Data Extract—Download Selection. Available at http://unstats.un.org/unsd/cdb/cdb_advanced_data_extract_fm.asp?HYrID=1995&HYrID=1996&HYrID=1997&HYrID=1998&HYrID=1999&HYrID=2000&HYrID=2001&HYrID=2002&HYrID=2003&HYrID=2004&HYrID=2005&HSrID=3520%2C3530&HCrID=404&continue=Continue+%3E%3E (accessed 11 April 2008).

University of California Delivers. Leaf color chart: a cost-effective tool for nitrogen management [Online]. Available at http://ucanr.org/delivers/impactview.cfm?impactnum=421 (accessed 23 February 2008).

Wikipedia. 2008. Kenya [Online]. Available at http://en.wikipedia.org/wiki/Kenya (accessed 10 April 2008).

Appendix I: Field Result Tables

α = .05	Location	Treatment	Location x Treatment	Level of Transformation
	---------------------------- Prob > F	-----------------------------		
Yield (kg/ha)	0.8484	0.0352*	0.4143	—
Plant Height (cm)	0.0206*	0.1463	0.2691	—
Leaf Color (1-8)	0.0173*	< 0.0289*	0.0289*	—
Soil Bulk Density	0.0003*	0.4134	0.6830	—

There was a Location*Treatment combined effect for leaf color, because the treatment difference was more significant at Farm B and C
D (F) > C (F) > B (F) > A (F) > D (M) >> A (M) > B (M) > C (M)

R1-Field

Location	Plant Height (cm)		Leaf Color (1-8)	
Farm A	84.80	b	5.48	b
Farm B	118.77	a	5.67	b
Farm C	95.85	b	5.38	b
Farm D	98.28	b	6.75	a

Treatment	Plant Height (cm)		Leaf Color (1-8)	
Fertilizer	104.63	a	6.94	a
Manure	94.23	a	4.70	b

Yield (Mg/ha)

Location	Yield (14% Moisture)	
Farm C	3.09	a
Farm D	3.21	a

Appendix II: Ear Leaf Tissue Analysis Summary

R1 Maize Ear Leaf Tissue Analysis

α = .05	Location	Treatment	Location x Treatment	Level of Transformation
	---------------------------- Prob > F	----------------------------		
Total N (%)	0.0009*	< 0.0001*	0.2785	—
P (mg/kg)	0.0006*	0.0002*	0.3968	—
K (mg/kg)	0.0436*	0.3053	0.8443	—
Ca (mg/kg)	< 0.0001*	0.0024*	0.2893	—
Mg (mg/kg)	< 0.0001*	0.0060*	0.0942	-1
S (mg/kg)	< 0.0001*	0.0007*	0.3560	—
Fe (mg/kg)	0.0279*	0.9583	0.4751	-1
Zn (mg/kg)	< 0.0001*	0.0378*	0.3999	—

R1—Plants

Location	% N		P (mg/kg)		K (mg/kg)		Ca (mg/kg)	
Farm A	2.03	a	1751.17	b	21005.4	a	3519.36	bc
Farm B	1.69	b	2341.27	a	20165.3	a	3122.32	c
Farm C	1.65	b	2144.63	a	18757.1	ab	4557.39	b
Farm D	2.23	a	1660.96	b	16134.3	b	6698.62	a

Location	Mg (mg/kg)		S (mg/kg)		Fe (mg/kg)		Zn (mg/kg)	
Farm A	893.48	c	1388.67	b	258.80	b	15.52	bc
Farm B	1353.92	b	1200.53	c	367.51	a	17.75	b
Farm C	1396.09	b	1383.85	b	377.35	a	23.51	a
Farm D	2265.81	a	1762.94	a	447.68	a	14.85	c

Appendix III: Soil Analysis at Time of Planting

Analysis conducted by KEPHIS in Kitale, Kenya

	Field A 0-15 cm	Field A 15-30 cm	Field B 0-15 cm	Field B 15-30 cm	Field C 0-15 cm	Field C 15-30 cm	Field D 0-15 cm	Field D 15-30 cm
pH (H_2O) 1:2.5	5.62	5.58	5.68	5.78	5.66	5.91	5.50	5.50
Total N (%)	0.16	0.21	0.27	0.19	0.20	0.22	0.30	0.29
Total C (%)	0.68	0.68	0.62	0.58	0.70	0.58	1.44	1.04
Available P (ppm)	4.03	5.94	271.75	19.90	11.81	5.30	17.52	6.41
K (%)	0.24	0.22	0.74	0.72	0.42	0.24	0.42	0.16
Ca (%)	5.06	5.47	6.28	6.28	7.09	7.49	8.10	6.68
Mg (%)	1.42	0.91	2.84	2.48	2.27	2.65	2.65	2.07
Mn (%)	0.78	1.03	1.05	0.95	1.04	0.88	0.70	0.70
Na (%)	0.69	0.51	0.53	0.67	0.43	0.45	0.37	0.39
Cu (ppm)	2.62	2.61	1.67	1.81	1.93	2.50	1.24	1.38
Fe (ppm)	23.35	25.76	33.00	23.70	18.69	21.89	20.95	18.52
Zn (ppm)	7.57	6.11	8.77	7.58	21.45	6.88	6.62	5.95

Appendix IV: Soil Chemical Analysis Summary

R1 15cm

α = .05	Location	Treatment	Location x Treatment	Level of Transformation
	---------------------------- Prob > F ----------------------------			
pH	0.0006*	0.0863	0.5401	—
Total N	0.0198*	0.2881	0.7116	-1
Total C	0.0338*	0.3268	0.8378	-1
Ca	0.0087*	0.2166	0.1993	—
Cu	0.0052*	0.3328	0.9298	—
Fe	0.7102	0.8262	0.9361	—
K	0.0016*	0.5251	0.6749	—
Mg	0.0024*	0.4781	0.3874	—
Mn	0.1770	0.5571	0.9359	—
P	0.1941	0.0857	0.4522	0

R1 30cm

α = .05	Location	Treatment	Location x Treatment	Level of Transformation
	---------------------------- Prob > F ----------------------------			
pH	0.0052*	0.2879	0.5506	-2
Total N	0.0316*	0.2483	0.9117	-1
Total C	0.0100*	0.3969	0.5247	-1
Ca	0.0003*	0.0109*	0.0456*	—
Cu	< 0.0001*	0.7107	0.1286	—
Fe	0.1017	0.9648	0.3722	—
K	< 0.0001*	0.0478*	0.7807	0
Mg	0.0068*	0.1496	0.2290	—
Mn	0.4238	0.5035	0.3947	0
P	0.3804	0.0532	0.3306	0

Harvest 15cm

α = .05	Location	Treatment	Location x Treatment	Level of Transformation
	---------------------------- Prob > F ----------------------------			
pH	0.0003*	0.9295	0.4069	—
Total N	< 0.0001*	0.5693	0.8304	0
Total C	< 0.0001*	0.1714	0.7551	0
Ca	0.0002*	0.9905	0.8091	—
Cu	< 0.0001*	0.7263	0.9176	—
Fe	< 0.0001*	0.2340	0.8095	—
K	0.1634	0.3764	0.6404	—
Mg	< 0.0001*	0.5409	0.7593	0
Mn	0.0046*	0.5731	0.5426	—
P	0.5153	0.7615	0.9102	—

Harvest 30cm

α = .05	Location	Treatment	Location x Treatment	Level of Transformation
	---------------------------- Prob > F -----------------------------			
pH	0.0023*	0.4316	0.9872	—
Total N	< 0.0001*	0.9799	0.5403	-1
Total C	< 0.0001*	0.7460	0.4484	-.5
Ca	0.0001*	0.6396	0.7339	-.5
Cu	< 0.0001*	0.8787	0.9182	—
Fe	0.0101*	0.9836	0.9771	—
K	< 0.0001*	0.5711	0.8945	0
Mg	< 0.0001*	0.5154	0.6076	-.5
Mn	0.0124*	0.8551	0.7995	—
P	0.4228	0.3185	0.9005	0

Soil pH

Treatment	15 cm R1		30 cm R1		15 cm H		30 cm H	
Fertilizer	5.22	a	5.19	a	5.03	a	5.08	a
Manure	5.51	a	5.32	a	5.04	a	5.23	a

Total C (g/kg)

Location	15 cm R1		30 cm R1		15 cm H		30 cm H	
Farm A	12.34	a	10.41	a	9.60	b	8.59	b
Farm B	7.57	b	7.01	b	—	—	6.83	c
Farm C	8.24	b	6.95	b	6.87	c	5.76	d
Farm D	—	—	—	—	20.72	a	18.34	a

Treatment	15 cm R1		30 cm R1		15 cm H		30 cm H	
Fertilizer	8.99	a	7.50	a	12.11	a	9.84	a
Manure	9.78	a	8.75	a	12.69	a	9.92	a

Total N (g/kg)

Location	15 cm R1		30 cm R1		15 cm H		30 cm H	
Farm A	0.81	a	0.67	a	0.58	b	0.51	b
Farm B	0.45	b	0.43	b	—	—	0.42	c
Farm C	0.56	ab	0.48	ab	0.45	c	0.39	c
Farm D	—	—	—	—	1.34	a	1.21	a

Treatment	15 cm R1		30 cm R1		15 cm H		30 cm H	
Fertilizer	0.57	a	0.47	a	0.78	a	0.64	a
Manure	0.64	a	0.58	a	0.79	a	0.63	a

P (mg/kg)

Location	15 cm R1		30 cm R1		15 cm H		30 cm H	
Farm A	10.63	a	4.68	a	8.33	a	6.68	a
Farm B	23.35	a	11.69	a	—	—	7.23	a
Farm C	28.31	a	12.47	a	7.15	a	4.81	a
Farm D	—	—	—	—	8.20	a	5.85	a

Treatment	15 cm R1		30 cm R1		15 cm H		30 cm H	
Fertilizer	27.50	a	14.77	a	7.75	a	6.82	a
Manure	15.03	a	4.45	a	8.03	a	5.46	a

K (mg/kg)

Location	15 cm R1		30 cm R1		15 cm H		30 cm H	
Farm A	103.83	b	88.67	b	97.71	a	56.21	c
Farm B	257.84	a	312.13	a	—	—	336.28	a
Farm C	122.84	b	93.27	b	96.95	a	82.52	bc
Farm D	—	—	—	—	134.26	a	106.29	b

Treatment	15 cm R1		30 cm R1		15 cm H		30 cm H	
Fertilizer	152.17	a	140.05	b	101.86	a	136.72	a
Manure	170.83	a	189.33	a	117.42	a	153.94	a

Ca (mg/kg)

Location	15 cm R1		30 cm R1		15 cm H		30 cm H	
Farm A	483.67	b	487.75	b	329.87	b	322.58	c
Farm B	625.28	b	561.80	b	—	—	523.40	b
Farm C	909.75	a	1096.41	a	691.64	a	951.63	a
Farm D	—	—	—	—	879.12	a	755.11	ab

Treatment	15 cm R1		30 cm R1		15 cm H		30 cm H	
Fertilizer	612.17	a	577.43	b	633.99	a	610.55	a
Manure	733.63	a	853.21	a	633.09	a	665.81	a

At 30 cm R1, there was a Location*Treatment Interaction effect, because at Farm B the manure treatment was slightly less than from the fertilizer treatment.

Fe (mg/kg)

Location	15 cm R1		30 cm R1		15 cm H		30 cm H	
Farm A	102.12	a	94.90	a	88.31	b	83.33	b
Farm B	95.82	a	81.76	a	—	—	72.82	b
Farm C	105.36	a	111.31	a	84.23	b	83.89	b
Farm D	—	—	—	—	123.75	a	116.60	a

Treatment	15 cm R1		30 cm R1		15 cm H		30 cm H	
Fertilizer	102.16	a	95.76	a	96.25	a	89.07	a
Manure	100.04	a	96.22	a	101.28	a	89.25	a

Cu (mg/kg)

Location	15 cm R1		30 cm R1		15 cm H		30 cm H	
Farm A	2.34	a	2.34	a	2.01	a	2.14	a
Farm B	1.01	b	0.74	c	—	—	0.65	c
Farm C	1.16	b	1.39	b	0.93	b	1.11	b
Farm D	—	—	—	—	1.10	b	1.13	b

Treatment	15 cm R1		30 cm R1		15 cm H		30 cm H	
Fertilizer	1.36		1.52	a	1.34	a	1.26	a
Manure	1.65		1.46	a	1.36	a	1.25	a

Mg (mg/kg)

Location	15 cm R1		30 cm R1		15 cm H		30 cm H	
Farm A	45.74	b	38.30	b	29.06	b	19.61	b
Farm B	150.04	a	127.68	a	—	—	113.77	a
Farm C	103.11	a	124.66	a	79.94	a	90.52	a
Farm D	—	—	—	—	106.77	a	85.29	a

Treatment	15 cm R1		30 cm R1		15 cm H		30 cm H	
Fertilizer	92.79	a	80.72	a	71.29	a	75.83	a
Manure	106.47	a	113.04	a	72.56	a	78.76	a

Mn (mg/kg)

Location	15 cm R1		30 cm R1		15 cm H		30 cm H	
Farm A	137.67	a	141.27	a	161.62	a	132.32	a
Farm B	157.44	a	124.35	a	—	—	106.76	ab
Farm C	187.65	a	162.55	a	137.42	a	87.62	b
Farm D	—	—	—	—	95.24	b	73.14	b

Treatment	15 cm R1		30 cm R1		15 cm H		30 cm H	
Fertilizer	154.72	a	147.16	a	135.23	a	98.89	a
Manure	167.11	a	138.27	a	127.62	a	101.02	a

Appendix V: Soil Physical Analysis

Field-Trt.-Timing	Water Stable Aggregate (%)						MWD
	4.75 mm	2 mm	1 mm	.5 mm	.25 mm	Total	(mm)
A – Fertilizer – R1	3.67	7.63	12.02	26.60	28.24	78.16	0.98
A – Fertilizer – H	8.10	7.14	10.98	25.13	24.13	75.48	1.20
A – Manure – R1	11.38	11.76	12.24	26.38	20.89	82.65	1.58
A – Manure – H	3.07	8.01	10.84	24.68	25.59	72.19	0.91
B – Fertilizer – R1	6.92	8.93	13.97	29.51	19.55	78.88	1.25
B – Fertilizer – H	0.18	3.28	10.29	26.57	25.03	65.35	0.57
B – Manure – R1	3.14	10.67	19.40	27.71	18.82	79.74	1.13
C – Cont – R1 and H	3.11	8.81	11.59	20.90	26.79	71.20	0.93
C – Fertilizer – R1	8.74	7.49	8.68	17.83	24.54	67.28	1.17
C – Fertilizer – H	3.33	16.53	13.22	20.79	18.88	72.75	1.20
C – Manure – R1	17.11	9.96	9.96	17.39	18.39	72.81	1.78
C – Manure – H	4.03	15.42	9.96	19.39	21.71	70.51	1.15
D – Fertilizer – H	53.53	15.52	8.53	6.51	3.69	87.78	4.13
D – Manure – H	46.45	13.26	8.96	9.38	5.58	83.63	3.63

R1

	Fertilizer Treatment		Manure Treatment	
Location	WSA (%)	MWD (mm)	WSA (%)	MWD (mm)
Farm A	78.16	0.98	82.65	1.58
Farm B	78.88	1.25	79.74	1.13
Farm C	67.28	1.17	72.81	1.78

Soil Bulk Density at Harvest

Location	Bulk Density (g/cm^3)	
Farm A	1.10	ab
Farm B	1.29	bc
Farm C	1.49	c
Farm D	0.92	a

Treatment	Bulk Density(g/cm^3)	
Fertilizer	1.17	a
Manure	1.23	a

Appendix VI: Monthly Rainfall and Average Temperatures

Data taken from Kakamega Meteorological Department's Monthly Weather Summaries

March 2008	Maximum Mean Temperature	29.1 ºC
	Minimum Mean Temperature	14.8 ºC
	Total Rainfall for Month	138.7 mm
	Total Evaporation for Month	151.4 mm
	Number of Rainy Days	19
April 2008	Maximum Mean Temperature	27.7 ºC
	Minimum Mean Temperature	14.5 ºC
	Total Rainfall for Month	236.1 mm
	Total Evaporation for Month	132.4 mm
	Number of Rainy Days	17
May 2008	Maximum Mean Temperature	27.1 ºC
	Minimum Mean Temperature	14.9 ºC
	Total Rainfall for Month	263.9 mm
	Total Evaporation for Month	127.5
	Number of Rainy Days	19
June 2008	Maximum Mean Temperature	26.2 ºC
	Minimum Mean Temperature	14.1 ºC
	Total Rainfall for Month	127.7 mm
	Total Evaporation for Month	103.4 mm
	Number of Rainy Days	15
July 2008	Maximum Mean Temperature	25.9 ºC
	Minimum Mean Temperature	13.9 ºC
	Total Rainfall for Month	199.3 mm
	Total Evaporation for Month	111.2 mm
	Number of Rainy Days	21
August 2008	Maximum Mean Temperature	26.4 ºC
	Minimum Mean Temperature	13.8 ºC
	Total Rainfall for Month	252.4 mm
	Total Evaporation for Month	132.4 mm
	Number of Rainy Days	24